Overview of PAMS Meteorological Monitoring Requirements

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ABSTRACT

The Photochemical Assessment Monitoring Station (PAMS) requires the incorporation of surface and upper air meteorological instrumentation. The platform for the surface instrumentation is a 10 m tower. The variables to be collected include horizontal wind speed, horizontal wind direction, air temperature, relative humidity, solar radiation, and barometric pressure. Upper air data may be acquired using a variety of platforms which include aircraft, tall towers, tethered and expendable radiosondes, and ground-based remote profilers. The variables to be collected include profiles of horizontal wind speed and direction, vertical wind speed, and air temperature. In addition, the mixing layer height should be determined from the upper air data. This paper summarizes the meteorological sensor requirements for PAMS which are not specifically addressed in the Code of Federal Regulations (40 CFR Part 58).

INTRODUCTION

The United States Environmental Protection Agency (EPA) has revised the ambient air quality surveillance regulations in Title 40 Part 58 of the Code of Federal Regulations (EPA, 1993). 40 CFR Part 58 requires the States to establish a network of Photochemical Assessment Monitoring Stations (PAMS) in ozone nonattainment areas which are classified as serious, severe, or extreme. Each PAMS must include provisions for enhanced monitoring of ozone and its precursors such as nitrogen oxides and volatile organic compounds. In addition, surface and upper air meteorological data must be acquired. EPA's authority for the enhanced monitoring regulations is provided for in Title I, Section 182 of the Clean Air Act Amendments of 1990.

The importance of a high quality meteorological data base for these nonattainment areas can not be overstated. These data are necessary to assist in the development and evaluation of new ozone control strategies, emissions tracking, trend analysis, exposure assessment, and numerical modeling (EPA, 1991). However, guidance is not provided in 40 CFR Part 58 on the specification of meteorological instrumentation that is to be used for PAMS. The regulation references two documents which are supposed to specify instrument type, characteristics, siting, and other quality assurance and quality control issues. The first is the *Technical Assistance Document for Sampling and Analysis of Ozone Precursors* (EPA, 1991). This document (TAD) was written to provide direction on sampling and analysis methodology for Regional, State, and local EPA personnel involved in enhanced ozone monitoring activities. The second is the *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements* (EPA, 1989). Unfortunately, the current version of the TAD lacks the specifics needed to establish a meteorological monitoring system for PAMS. The Quality Assurance Handbook, however, contains a great deal on instrument specifications, but no detail on how to apply it to PAMS.

This paper will attempt to consolidate the available EPA guidance on meteorological monitoring and apply it to PAMS. Where guidance is absent, this paper will try to make recommendations on instrument types and procedures.

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SURFACE METEOROLOGICAL INSTRUMENTATION

Guidance for making surface meteorological measurements is provided in several EPA documents and is summarized in this paper. They include: *On-Site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources* (EPA, 1981); *Ambient Monitoring Guidelines for Prevention of Significant Deterioration* (EPA, 1987a); *On-Site Meteorological Program Guidance for Regulatory Modeling Applications* (EPA, 1987b); and *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements* (EPA, 1989). Additional information is provided in the *Instructor's Handbook on Meteorological Instrumentation* (NCAR, 1985). The guidance found in all of these references has it roots in the *Guide to Meteorological Instruments and Methods of Observation* (WMO, 1983).

The surface meteorological variables which are required to be measured at each PAMS site include horizontal wind speed and wind direction, ambient air temperature, relative humidity, solar radiation, and barometric pressure. Since these variables need to be measured at different heights, a tower is usually the most advantageous measurement platform. For PAMS, a 10 m tower is required.

The most preferable type of tower is the open lattice or open grid variety since it creates the least amount of turbulence. The tower must be rugged enough so that it can be climbed safely to install and service the instruments. Folding or collapsible towers are desirable since they allow the instruments to be serviced at the ground. The tower should be sufficiently rigid to hold the instruments in proper orientation at all times. Solid structures such as stacks, water storage tanks, grain elevators, and cooling towers should be avoided since they can create significant wind flow distortions.

The primary objective of instrument siting (horizontal and vertical probe placement) and exposure (spacing from obstructions) is to place the sensor in a location where it can make precise measurements that are representative of the general state of the atmosphere in that region under study. The choice of a site must be made with a complete understanding of the regional geography, the sources being investigated, and the potential uses of the data being collected. Ideally, the tower should be located in an open level area. In terrain with significant topographic features, different levels of the tower may be under the influence of different meteorological regimes at the same time. If this is the case, such conditions should be well documented. Secondary considerations such as accessibility and security must be taken into account, but should not be allowed to compromise data quality.

These basic meteorological variables should be sampled at least once every 10 seconds and recorded digitally by a data logger as one hour averages. The observation time should correspond to the time at the end of the averaging period (i.e., 0200, 0300, etc.) and be recorded as local standard time. The clock for the data acquisition system should have an accuracy of ±1 minute per week.

Wind Speed and Direction

Horizontal wind speed ($m\ s^{-1}$) and wind direction (degrees clockwise from geographical north) are the most important meteorological variables needed to understand transport and dispersion processes. These two variables help determine the initial dilution experienced by a plume, transport direction, and atmospheric stability parameters such as the standard deviation of the wind direction (F_2).

The most commonly used instruments for measuring wind speed and direction in air quality studies are: Cup anemometer and wind vane, propeller anemometer mounted on the front of a wind vane, and two horizontal propellers mounted at right angles to each other.

The standard exposure of a wind sensor over level, open terrain is 10 m above the ground. Open terrain is defined as an area where the horizontal distance between the instrument and any obstruction is at least ten times the height of that obstruction. An obstruction may be man-made (e.g., building) or natural (e.g., trees). Where a standard exposure is unobtainable, the anemometer should be installed at a height that its indications are reasonably unaffected by local obstructions and represents, as far as possible, what the wind at 10 m would be if there were no obstructions in the vicinity.

The wind sensor should be mounted on a mast at a distance of at least one tower width projecting vertically from the top of the tower. If the tower is greater than 10 m, then the wind sensor should be mounted on a boom projecting horizontally out from the tower. Precautions must be taken to ensure that the wind measurements are not unduly influenced by the tower. Turbulence in the immediate wake of the tower (even a lattice type) can be severe. Therefore, the sensor should be located at a horizontal distance of at least twice the maximum width of the tower away from the nearest point on the tower. The boom should project into the direction which provides the least distortion for the most important wind direction. For example, the boom should be aligned in a northwesterly or southeasterly direction if the predominant wind is from the southwest.

A sensor with high accuracy at low wind speeds is desirable since air pollution concentrations are inversely proportional to wind speed. A low starting threshold speed is required for PAMS applications. Light weight molded plastic or polystyrene foam should be employed for cups, propeller blades, and tail fins to achieve a starting speed of # 0.5 m s^{-1}. Wind speed for a cup or propeller anemometer should be accurate to ±0.2 m s^{-1} + 5% of observed speed from 0.5 to 5 m s^{-1}. At wind speeds greater than 5 m s^{-1}, the accuracy should be 5% of the observed speed, never to exceed ±2.5 m s^{-1}. Resolution should be # 0.1 m s^{-1}. The distance constant (the distance of passage through the cup or propeller required for sensor to indicate a 63% step change in the wind speed) should be # 5 m. The wind direction should be accurate to ±5^o with a resolution of # 1^o. The starting speed should be # 0.5 m s^{-1} from a 10^o deflection. The delay distance (50% recovery from a 10^o deflection) should be # 5 m and the damping ratio should lie between 0.4 and 0.7.

Air Temperature

Ambient air temperature (^{o}C) measurements are used for estimating buoyancy flux in plume rise computations and for converting pollutant concentrations. The most common type of sensor used is the platinum temperature probe (RTD). This type of sensor provides an accurate measurement with a stable calibration over a wide temperature range.

The temperature probe should be mounted on the tower 2 m above the ground and away from the tower at a distance of at least one tower width from the closest point on the tower. This height is consistent with WMO (1983) standard monitoring procedures. The measurement should be made over a plot of open, level ground at least 9 m in diameter. The ground surface should be covered with non-irrigated or unwatered short grass or, in areas which lack a vegetation cover, natural earth. The surface must not be concrete, asphalt, or oil-soaked. If there is a large paved area nearby, the sensor should be at least 30 m away from it. Areas to avoid also include large industrial heat sources, roof tops, steep slopes, hollows, high vegetation, swamps, snow drifts, standing water, and air exhausts (e.g., tunnels and subway entrances). The probe should be located at a distance from any obstructions of at least four times their height.

The air temperature probe should have an accuracy of ±0.5 ^{o}C over a range of -20 to +40 ^{o}C with a resolution of # 0.1 ^{o}C. The time constant (63%) should be # 60 seconds. Solar radiation is the largest source of error for ambient air temperature measurements. Adequate shielding is needed to provide a representative measurement of the atmosphere. The best type of shield is one which provides forced aspiration at a rate of $ 3 m s^{-1}. Ideally, the radiation shield should block the sensor from view of the sun, sky, ground, and surrounding objects. The shield should reflect all incident radiation and not reradiate any of that energy towards the sensor. The probe must also be protected from precipitation and condensation, otherwise evaporative effects will lead to a depressed temperature measurement (i.e., wet bulb temperature).

Relative Humidity

Atmospheric humidity is expressed in various ways. It may be represented as vapor pressure (hPa), dew point temperature (^{o}C), specific humidity (g kg^{-1}), mixing ratio (g kg^{-1}), absolute humidity (g m^{-3}), or relative humidity (%RH). All variables except the relative humidity provide a complete specification of the amount of water vapor in the atmosphere. However, any of these variables can easily be derived from the relative humidity given the ambient air temperature and barometric pressure.

There are various methods of measuring atmospheric humidity. However, the emergence of thin-film technology has produced relative humidity sensors which are fairly accurate, compact, and inexpensive. They are also becoming increasingly common as they lend themselves to easy installation for automatic recording stations.

The relative humidity sensor should be installed with the same siting considerations given to the air temperature sensor. The probe should be housed in the same aspirated radiation shield at 2 m above the ground. The accuracy should be at least ±3 %RH over a temperature range of -20 to +40 °C with a resolution of # 0.5 %RH or better. The time constant (63%) should be # 60 seconds.

The thin-film elements of the humidity probe must be protected from contaminants such as salt, hydrocarbons, and other particulates. These pollutants can easily corrupt the sensing element and lead to failure of the probe. The best protection is the use of a porous membrane filter which allows the passage of ambient air and water vapor while keeping out particulate matter.

Solar Radiation

Solar (sometimes call shortwave) radiation is the electromagnetic radiation of the sun which is represented as an energy flux (W m^{-2}). Solar radiation measurements are useful for heat flux calculations, estimating atmospheric stability and understanding photochemical reactions (i.e., ozone generation). 97% of the solar radiation incident at the top of the earth's atmosphere lies between 0.29 and 3.0 :m. The solar spectrum is comprised of ultraviolet radiation (0.29 to 0.40 :m), visible light (0.40 to 0.73 :m), and near-infrared (0.73 to 4.0 :m) radiation. A portion of this energy penetrates through the atmosphere and is received at the earth's surface. The rest is scattered and/or absorbed by gas molecules, aerosols, cloud droplets, and cloud crystals. The instrument needed for measuring this variable covering the range of the solar spectrum is a pyranometer. This sensor measures global (direct and diffuse) radiation when installed facing upwards in a horizontal plane tangent to the earth's surface.

Solar radiation measurements should be taken in a location with an unrestricted view of the sky which is free from any obstructions. There should be no object above the horizontal plane of the sensor that could possibly cast a shadow or reflect light on it (including the tower). In addition, the pyranometer should not be placed near light colored walls or artificial sources of radiation. In practice, the horizon should not exceed 5°, especially from the east-northeast through the south to the west-northwest. A 5° horizon will obstruct only about 1% of the global radiation and thus can be considered negligible.

There is no height requirement for a pyranometer. A tall platform or a roof top usually make ideal locations for sensor placement. If such facilities are not readily available, then the best strategy is to place the instrument directly south of the tower and its guy wires. Regardless of where the pyranometer is installed, it is important that the instrument be level with the horizontal plane to better than 1°. Any tilt from the horizontal plane may introduce significant errors (see Katsaros and DeVault, 1986). Most pyranometers usually have a circular spirit level attached so that proper leveling may be achieved.

EPA accuracy requirement for a solar radiation measurements is ±5% with a resolution of # 10 W m^{-2}. It is desirable to obtain a sensor which meets the WMO criteria of a Secondary Standard or First Class pyranometer (Table 1) if reliable heat flux and stability parameters are to be calculated.

Barometric Pressure

Very little EPA guidance is available for acquiring barometric pressure (hPa) because it is not generally required in many air pollution applications. However, time series of these data are quite useful in examining trends in the weather on the order of several days or more. It is also an important variable which is used in the calculation of thermodynamic quantities such as air density, absolute humidity and potential temperature. Note that standard sea level pressure is 1013.25 hPa.

There are numerous commercially available pressure transducers which range widely both in price and performance. Most of these sensors are capable of delivering barometric pressure with an overall accuracy of ±1.0 hPa with a resolution of # 0.1 hPa as required by EPA guidance. While no guidance is available for response time, it should be # 60 seconds.

The barometric pressure does not have to be obtained at 10 m as suggested in the TAD. The sensor can be placed at the base of the tower or inside a shelter. Ideally, the sensor should be placed at 2 m above the ground. If a value for the pressure at 10 m (p_{10}) is desired, then a simple correction to the 2 m pressure (p_2) may be applied by using the hypsometric equation

$$p_{10} = p_2 e^{\frac{g(z_2 - z_{10})}{R_d T_v}}$$

where z_2 and z_{10} are 2 and 10 m, respectively, g is the acceleration due to gravity (9.81 m s^{-2}), R_d is the universal gas constant for dry air (287.05 J kg^{-1} K^{-1}), and T_v is mean virtual air temperature (K) in the layer between z_2 and z_{10} which is computed by using

$$T_v = T(1 + 0.61w)$$

where T is the mean ambient air temperature (K) between z_2 and z_{10}, and w is the mixing ratio (g g^{-1}). The decrease in pressure between the 2 and 10 m is on the order of 1 hPa for a typical ambient air temperature of 20 ^{o}C and mixing ratio of 15 g kg^{-1}. Altitude of the station above mean sea level and the height of the pressure sensor above ground level should be documented in the event that sea level pressure needs to be computed using the hypsometric equation.

If the pressure sensor is placed indoors, accommodations should be made to vent the pressure port to the outside environment. One end of a tube should be attached to the sensor's pressure port and the other ended vented to the outside of the trailer or shelter so that pressurization due to the air conditioning or heating system is avoided. The wind can often cause dynamical changes of pressure in a room where a sensor is placed. These fluctuations may be on the order of 2 to 3 hPa when strong or gusty winds prevail.

UPPER AIR METEOROLOGICAL INSTRUMENTATION

40 CFR Part 58 requires the measurement of upper air meteorology. However, the regulation does not contain specific details on which variables need to be measured. The TAD, however, does suggest that profiles of horizontal wind velocity, vertical wind velocity, and air temperature be acquired. Also needed is an estimate of the mixing layer height and stability class of the atmospheric boundary layer. There is a special emphasis on knowing the depth of the atmospheric boundary layer. The mixing height is an important variable in many EPA regulatory models since it determines the vertical extent of turbulent mixing of pollutants during neutral and unstable atmospheric conditions.

There are a variety of measurement platforms which can be used to acquire these data. They include aircraft, towers, tethered and expendable balloon systems, and ground-based remote profilers. As with any measurement system, each has many advantages and disadvantages.

Unfortunately, the temporal and spatial density of these variables have not been clearly defined. In addition, the number of upper air stations needed for each nonattainment area is also uncertain. The TAD infers that there should be at least one upper air station for each area. Many of the EPA documents cited in this paper lack the necessary guidance for acquiring upper air information. Until further guidance is established by EPA, sampling of upper air meteorology is left to the discretion of the States. The information presented below provides recommendations for sampling platforms; each approach is briefly discussed.

Aircraft

Aircraft are the ultimate mobile observation station. They are capable of traversing large horizontal and vertical areas in a relatively short period of time. This platform can be equipped with meteorological instrumentation and an assortment of chemical sensors. Traditionally, aircraft are used for intense episodic field studies which often focus on model evaluation. Lenschow (1986) provides an excellent overview of aircraft measurements in boundary layer applications. While an aircraft can provide detailed atmospheric observations over large areas, the total sampling time is relatively short because of fuel considerations. Aircraft may also be subject to Federal Aviation Administration (FAA) restrictions on flight paths over urban areas. In addition, the operating cost for this type of platform is extremely expensive. Therefore, aircraft are not considered feasible for routine PAMS applications.

Tall Towers

Tall towers, usually in excess of 100 m, sometimes are used in the assessment of local meteorological conditions, diffusion studies, and micro-meteorological research projects. In many instances, it is best to take advantage of existing towers since installation of new platforms incur large costs. The main disadvantage of a tall tower is that it can not determine the mixing layer height under most daytime convective conditions since the atmospheric boundary layer commonly exceeds 1000 m. Maintenance costs can also be high since access to the instrumentation is sometimes difficult. The logistics of siting a tower in an urban setting can also be quite formidable. While an instrumented tall tower may be able to resolve the lowest part of the atmospheric boundary layer, it is not the most ideally suited upper air platform for PAMS.

Balloon Systems

Balloon based measurement systems offer a relatively inexpensive means of measuring upper air meteorology. There are two types: Radiosonde (sometimes called rawinsonde) and tethersonde.

The radiosonde was designed to be reliable, robust, light weight, and small in bulk. Because this package is expendable, it is mass produced at low cost. The radiosonde is comprised of sensors, a tracking device, and a radio transmitter. This sensor package is suspended from a hydrogen or helium balloon which is released from the surface. Air temperature is measured with a bimetallic strip, ceramic semi-conductor, or a wire resistor. The relative humidity is acquired with the use of a carbon hygristor or a thin-film capacitive chip. The barometric pressure is obtained with the use of aneroid capsules. Ground-based radar is used to determine horizontal wind speed and direction. The radiosonde is capable of easily traversing the depth of the troposphere and reaching well into the stratosphere.

A tethersonde system is comprised of a tethered balloon with several sonde packages attached to the line. Variables measured include horizontal wind speed and direction, air temperature, relative humidity, and barometric pressure. These data are telemetered to the ground by radio or conductors incorporated within the tethering cable. The tethersonde system is capable of achieving altitudes up to 1000 m. However, this system can only operate in light to moderate wind conditions (5 m s^{-1} at the surface, 15 m s^{-1} aloft). A tethered balloon may also pose as an aviation hazard and is subject to FAA regulations. A permit must be obtained for permission to operate such a system. The main disadvantage for these balloon systems is that they can be very labor intensive, especially if data are needed on an hourly basis.

Remote Profilers

In recent years, remote sensing has played an increasingly important role in atmospheric boundary layer studies. Ground-based remote profilers have gained a reputation as effective tools for acquiring upper air information. However, while these profiling systems have been approved and used to develop meteorological databases required as input for dispersion models, there is a distinct void in terms of guidance needed to help potential users and the regulatory community. Because of their unique nature and constant evolution, the EPA guidance for profilers is more generic than that which already exists for many well established in-situ meteorological sensors. However, efforts are underway to provide more clearly defined guidance and standard operating procedures and will appear in the next edition of the *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements*.

There are two basic types of wind profiling systems. The first type is a radar which transmits a 915 MHz electromagnetic signal and has a range of approximately 90 to 3000 m with a vertical resolution of 75 to 150 m. The second type is a sodar (sound detection and ranging) which transmits a 2 to 5 KHz acoustic signal and has a range of about 60 to 600 m with a resolution of about 50 m. Both systems transmit their respective signals in pulses. Each pulse is both reflected and absorbed by the atmosphere as it moves upwards. The vertical range of each pulse is determined by how high it can go before the signal becomes so weak that the energy reflected back to the antenna can no longer be detected. That is, as long as the reflected pulses can be discerned from background noise, meaningful wind velocities can be obtained by comparing the Doppler shift of the output signal to that of the return signal. The attenuation of the pulses are functions of signal type, signal power, and atmospheric conditions. A radio acoustic sounding system

(RASS) utilizes a combination of electromagnetic and acoustic pulses to derive an air temperature profile in the range of about 90 to 1200 meters.

Siting of these profilers is sometimes a difficult task. Artificial and natural objects located near the sensors can potentially interfere with the transmission and return signals, thereby contaminating the wind velocity data. The acoustic pulses emitted by a sodar and a RASS are quite audible and could become a nuisance to residents who live near the installation site. However, the main advantage to these systems is that they can operate remotely for extended periods of times with no or very little supervision.

SUMMARY

The Photochemical Assessment Monitoring Station will require the incorporation of surface and upper air meteorological instrumentation. The surface variables include horizontal wind speed and direction, air temperature, relative humidity, solar radiation, and barometric pressure. Sensor specifications are summarized in Table 2. Upper air variables should include profiles of horizontal and vertical wind velocity, air temperature, and mixing height. Ranges and accuracies (based on surface sensor requirements) are given in Table 3. Personnel from State, Regional and local EPA agencies are strongly encouraged to comment on and recommend any improvements to these requirements so that high quality meteorological data may be obtained in these ozone nonattainment areas.

DISCLAIMER

This document has been reviewed in accordance with U. S. Environmental Protection Agency policy and approval for publication. Mention of trade names or commercial products does not constitute EPA endorsement or recommendation for use.

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Table 1
WMO (1983) Classification of Pyranometers

Characteristic	Units	Secondary Standard	First Class	Second Class
Resolution	$W\ m^{-2}$	±1	±5	±10
Stability	%FS $year^{-1}$	±1	±2	±5
Cosine Response	%	±3	±7	±15
Azimuth Response	%	±3	±5	±10
Temperature Response	%	±1	±2	±5
Nonlinearity	%FS	±0.5	±2	±5
Spectral Sensitivity	%	±2	±5	±10
Response Time (99%)	seconds	25	60	240

Table 2
Summary of sensor requirements for surface meteorological variables based on available EPA and WMO guidance.

Variable	Height (m)	Range	Accuracy	Resolution	Time / Distance Constants
Wind Speed	10	0.5 to 50 $m\ s^{-1}$	±5%	0.1 $m\ s^{-1}$	5 m (63% response)
Wind Direction	10	0 to 360°	±5°	1°	5 m (50% recovery)
Air Temperature	2	-20 to 40 °C	±0.5 °C	0.1 °C	60 s (63% response)
Relative Humidity	2	0 to 100 %RH	±3 %RH	0.5 %RH	60 s (63% response)
Solar Radiation	any	0 to 1200 $W\ m^{-1}$	±5%	10 $W\ m^{-2}$	60 s (99% response)
Barometric Pressure	2	800 to 1100 hPa	±1 hPa	0.1 hPa	60 s (63% response)

Table 3
Summary of sensor requirements for upper air meteorological variables based on available EPA and WMO guidance.

Variable	Range	Accuracy
Wind Speed	0 to 50 m s^{-1}	±1 m s^{-1}
Wind Direction	0 to 360^{o}	±10^{o}
Air Temperature	-20 to 40 ^{o}C	±0.5 ^{o}C
Relative Humidity[1]	0 to 100 %RH	±5 %RH
Barometric Pressure[1]	650 to 1050 hPa	±1 hPa
Altitude	0 to 3000 m	±1%

[1]While upper air relative humidity and barometric pressure data are not required for PAMS, they are desired measurements, especially for thermodynamic computations.